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Article

Exploring human body dynamics to optimize spatial arrangements in interior and landscape design

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Abstract: The interplay between human body dynamics (HBD) and spatial design (SD) is a crucial yet often overlooked factor in creating environments that optimize comfort, efficiency, and usability. This paper explores the application of HBD, including biomechanics, posture, gait, and balance, to the design of both interior and landscape spaces. Through analyzing body mechanics and movement patterns, this research aims to provide a framework for designers to create spaces that support natural human movement while reducing physical strain and enhancing user experience. This paper demonstrates how spatial arrangements can be optimized for various activities, user groups, and environments by utilizing gait analysis, motion capture, and force plate testing. Case studies from ergonomically designed office spaces, public transportation hubs, outdoor parks, and residential facilities illustrate the practical benefits of integrating HBD into SD. The research also identifies the limitations of current design practices, such as cost, complexity, and the lack of comprehensive data on diverse populations. Additionally, the paper explores future research opportunities, particularly the role of advancements in artificial intelligence, biomechanics, and wearable technology in creating dynamic, adaptive spaces that respond to user needs. The findings highlight the importance of SD that are visually appealing and aligned with users' physical and ergonomic needs, ensuring that both interior and landscape environments promote comfort, accessibility, and overall well-being.

Keywords: human body dynamics; spatial design; motion capture; biomechanics; artificial intelligence

1. Introduction

The relationship between human body dynamics (HBD) and spatial design (SD) has recently gained increasing attention, particularly in interior and landscape design [1,2]. As individuals interact with their environments daily, understanding the fundamental mechanics of body movement (BM), posture, balance, and gait becomes essential for creating spaces that are not only aesthetically pleasing but also functionally efficient [3,4]. HBD refers to the study of how the BM responds to forces, such as gravity and external resistances, and how these movements are influenced by SD [5]. By analyzing HBD, designers can optimize spaces to suit the natural flow of human movement better, enhancing comfort, reducing physical strain, and promoting overall well-being [6–8].

In interior and landscape design, the arrangement of physical elements—such as furniture, pathways, and structural features—directly impacts how individuals move through and experience a space [9]. Poorly designed environments can lead to awkward BM, fatigue, and discomfort, which in turn affect the functionality and usability of a space [10]. Conversely, well-designed spaces that consider HBD can enhance movement efficiency, support good posture, and provide a more intuitive interaction with the environment [11,12]. This integration of HBD into SD helps create environments that are accessible, comfortable, and adaptable to the diverse needs of users, including children, elderly individuals, and those with disabilities [13,14].

Recent technological advancements, including motion capture, gait analysis, and biomechanics, have provided designers with new tools to assess and incorporate HBD into their work [15,16]. By studying the range of motion, balance, and forces exerted by the HBD, designers can make data-driven decisions that improve indoor and outdoor environments [17]. For example, ergonomic furniture design, optimized walking paths, and the strategic use of surface materials all contribute to an individual's ability to move freely and safely within a space [18,19]. Moreover, considering dynamic SD based on activity levels can further enhance the functionality of a space, allowing for seamless transitions between different areas and activities [20]. This paper explores the intersection of HBD and SD, offering insights into how these principles can be applied to interior and landscape environments. The paper aims to provide a comprehensive framework for optimizing SD to support natural human movement by examining key concepts such as biomechanics, posture, gait, and balance. Through a combination of theoretical analysis, case studies, and practical recommendations, this research highlights the importance of designing spaces that align with the body's physical needs, ensuring comfort, accessibility, and user satisfaction in various settings.

This paper is organized into seven sections. It begins with the Theoretical Framework, covering key concepts of HBD and their relevance to design. HBD analysis follows, exploring methods like gait analysis with case studies. Application to interior design and landscape design discusses how human movement informs SD in indoor and outdoor environments. Design principles offer practical guidelines for integrating biomechanics into design and adapting for diverse users. Challenges and future directions address limitations and propose future research, followed by a conclusion summarizing the key findings and the importance of optimizing design for HBD.

The article is presented as follows: Section 2 presents the theoretical framework, Section 3 presents the methodology, Section 4 presents the analysis, and Section 5 concludes the paper.

2. Theoretical framework

2.1. HBD

HBD refers to studying how the human BM interacts with its physical environment. This field encompasses the analysis of body mechanics, the forces involved in movement, and the movement patterns related to posture, gait, and balance.

2.1.1. Biomechanics

Biomechanics is a core discipline within HBD that applies principles of mechanics—such as physics and engineering—to understand how the muscles, bones, and joints work together to create movement. This includes analyzing forces such as gravity and muscle-generated tension, as well as the effects of these forces on BM. Human movement can be described in planes and axes, as shown in the image. The BM is in three primary planes: sagittal, frontal, and transverse, each dividing the body into different sections. The sagittal plane divides the body into left and right halves, with movements such as flexion and extension typically occurring along this plane. The frontal plane divides the body into front and back sections, and movements such as abduction and adduction (e.g., moving limbs away from or toward the midline) occur in this plane. Lastly, the transverse plane divides the body into upper and lower halves, and rotational movements like twisting occur within this plane (**Figure 1**).

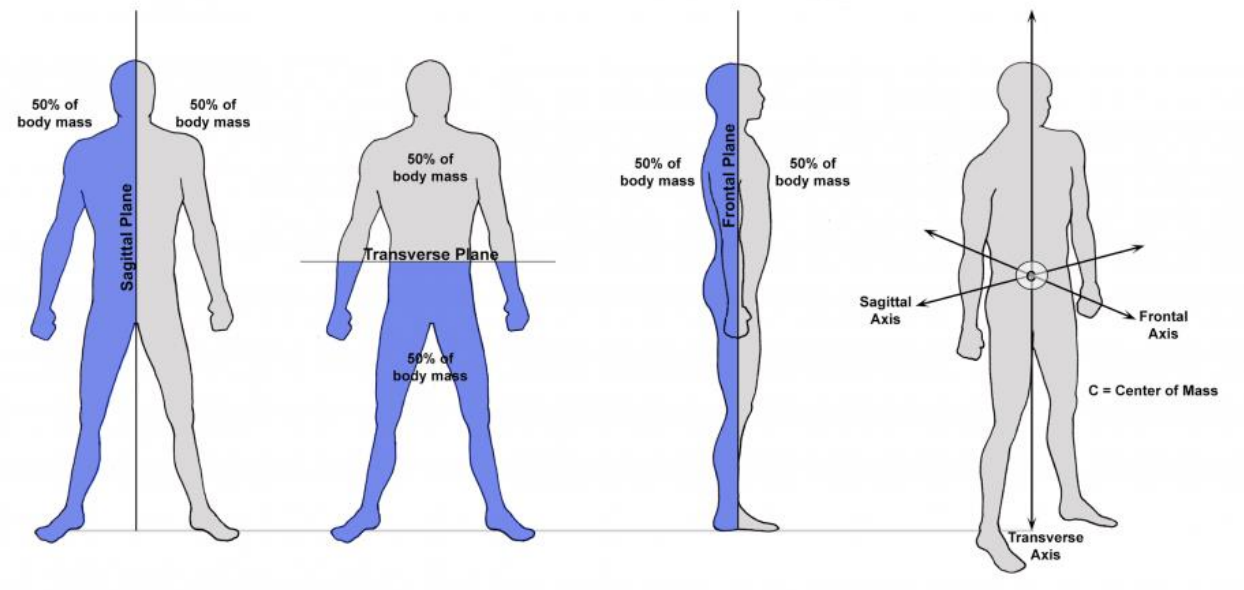

Figure 1. Planes of movement [21].

Corresponding to these planes are the axes of movement. Movements in the sagittal plane rotate around the frontal axis, movements in the frontal plane rotate around the sagittal axis, and movements in the transverse plane rotate around the vertical (longitudinal) axis. The image further illustrates how these planes and axes are interconnected with the body’s center of mass (C), emphasizing the balance and symmetry of human movement. Understanding the interaction of these planes and axes is crucial for optimizing SD, as it helps predict and accommodate human movement. For instance, when designing pathways or furniture layouts, it is essential to consider the natural motion arcs corresponding to these planes to ensure ease of movement, minimize physical strain, and enhance user comfort.

2.1.2. Kinematics and kinetics

The kinematics and kinetics are two key concepts within biomechanics. Kinematics describes motion, focusing on parameters like velocity, acceleration, and displacement without referencing the forces causing them. These relationships are mathematically expressed through sinusoidal equations represented as graphs in **Figure 2**. The following equations describe the relationships:

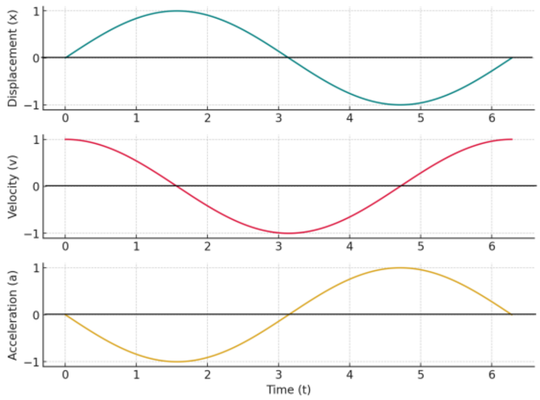

Figure 2. Displacement, velocity and acceleration.

(1) Displacement:

$$x(t) = A\sin(\omega t) \tag{1}$$

where A is the amplitude, ω is the angular frequency, and t is time.

(2) Velocity (the first derivative of displacement concerning time):

$$v(t) = A\omega\cos(\omega t) \tag{2}$$

Velocity reaches its maximum when displacement is zero and vice versa.

(3) Acceleration (the second derivative of displacement concerning time):

$$a(t) = -A\omega^2\sin(\omega t) \tag{3}$$

Acceleration is at its maximum when displacement is at its lowest point, showing the most significant force acting to return the object to equilibrium.

The Equations (1)–(3) highlight the cyclical nature of movement, as shown in the accompanying graph. As displacement increases or decreases following a sinusoidal pattern, velocity, and acceleration fluctuate in response, with velocity being zero at maximum displacement and acceleration reaching its peak when displacement is at its lowest. Understanding these kinematic relationships is vital in interior and landscape design. For instance, they predicted how humans move through space—whether walking through a room or navigating outdoor paths—and required knowledge of these motion dynamics. By applying these principles, designers can ensure that their SD accommodates the natural flow of movement, enhancing comfort and efficiency while reducing unnecessary physical strain.

Kinetics focuses on the forces and torques (**Figure 3**) that produce or are generated by motion, encompassing key elements such as muscle forces, gravity, and external resistances. While kinematics describes the BM's, kinetics provides a more profound understanding by analyzing the underlying causes of motion, which are crucial for comprehending how the BM interacts with its environment. In HBD, muscle forces are central to generating movement. Muscles contract and apply force on the skeletal system, enabling walking, lifting, or balancing actions. The magnitude and direction of these forces determine the type of movement and how effectively it can be performed. For example, during walking, muscles in the legs generate sufficient force to propel the body forward while maintaining stability.

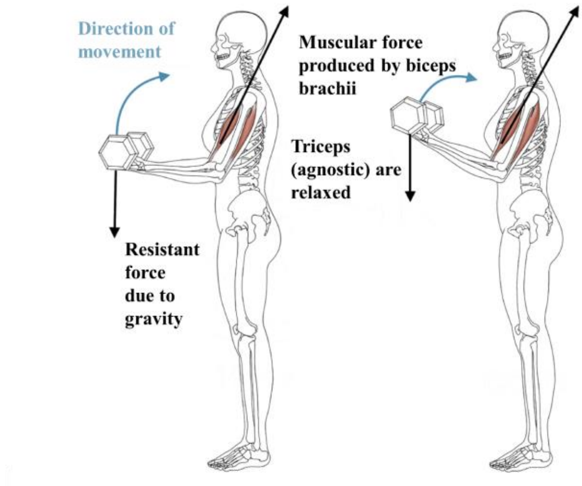

Figure 3. Force, torque, gravity, and resistance [22].

Gravity is another critical factor in kinetics. It continuously acts on the body, requiring counteracting forces from muscles and skeletal support to maintain posture and facilitate movement. When designing interior or landscape spaces, it's essential to consider how gravity interacts with the body in different positions, such as standing, sitting, or climbing stairs. Designers can optimize SD to minimize unnecessary muscle strain and improve comfort. External resistances, such as friction or applied loads, also influence movement. For instance, the surface materials used in pathways or flooring can affect friction, making movement easier or harder depending on the design.

Additionally, carrying weights or encountering obstacles introduces additional forces that the body must overcome, influencing both movement efficiency and the risk of injury. Torque, the rotational equivalent of force, also plays a vital role in kinetics. It occurs when forces cause rotation around a joint or pivot point. For instance, the force applied by the muscles around the knee joint creates torque, allowing the leg to rotate and produce forward movement. Understanding torque is essential for SD, especially when considering how people interact with objects, furniture, or elements like handrails and doorknobs involving rotational movement. By analyzing these forces and torques, designers can better understand how people move through and interact with spaces. For example, designing ergonomic furniture or creating walking paths that reduce external resistance and balance gravitational effects can significantly enhance comfort and efficiency in human movement. Therefore, kinetics is fundamental in creating spaces that support motion and improve overall user experience by accounting for the forces at play in HBD.

2.1.3. Posture

Posture refers to the alignment and position of the body at rest or during activity, and it plays a significant role in determining the efficiency, comfort, and overall health of movement. Proper posture (**Figure 4**) ensures that the body's joints, muscles, and skeletal structure are aligned to minimize stress on the body during both static and dynamic activities. Whether standing, sitting, or moving, posture directly influences how well the body can perform tasks and maintain balance. In HBD, posture is not just a static concept but is dynamically adjusted during various activities. For example, when walking, the posture shifts to balance the body's center of mass and reduce the impact on muscles and joints. Similarly, the alignment of the spine, hips, and shoulders is crucial for preventing strain on the back and neck while sitting.

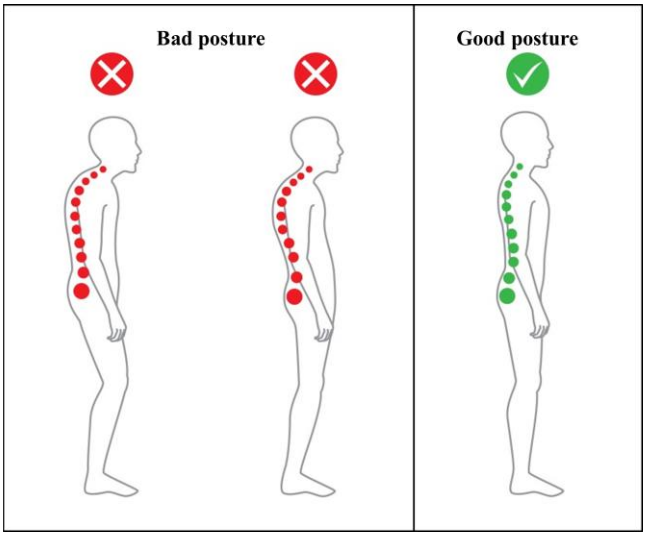

Figure 4. Good vs bad posture.

Poor posture can lead to significant discomfort and long-term strain on muscles, joints, and ligaments. The body may be forced into awkward or unnatural positions in spaces not designed with HBD in mind, such as improperly configured workspaces or poorly designed seating areas. Over time, this can cause muscle fatigue, joint stiffness, and even chronic pain. For instance, slouching while sitting at a desk can strain the neck and lower back muscles, leading to discomfort that worsens with prolonged activity. Spaces that don't accommodate proper posture can also affect movement efficiency. If furniture is too high or too low, or if walking paths are too narrow or irregular, the body has to exert more effort to maintain balance and alignment. This can reduce movement efficiency and lead to early fatigue, as the body must compensate for poor SD.

In contrast, well-designed spaces consider human posture and its impact on comfort and movement. Ergonomically designed furniture, for instance, provides support for the spine, reduces pressure on joints, and promotes natural alignment, allowing the body to remain comfortable and balanced. Similarly, pathways and open spaces allow smooth transitions between movements, which help maintain proper posture and minimize strain. In interior and landscape design, considering posture means creating environments that facilitate natural, relaxed positions for the body. This enhances comfort and improves the overall functionality of a space, ensuring that individuals can move and rest without putting unnecessary strain on their bodies.

2.1.4. Gait

Gait is the term used to describe the movement pattern during walking or running, focusing on the BM from one point to another. The study of gait involves analyzing the cycle of steps (**Figure 5**), which includes phases such as heel strike, mid-stance, and toe-off. Each phase of the gait cycle involves a complex interaction of muscles, bones, and joints working together to distribute weight evenly and maintain balance. Gait analysis is essential for understanding how individuals move through different spaces, particularly when optimizing interior and landscape design SD. During walking or running, the body undergoes repetitive cycles of movement that require efficient weight distribution. Poor alignment or improper movement can disrupt this cycle, leading to inefficient movement, strain, or injury. For example, if a pathway is uneven or has obstacles, the natural gait pattern may be interrupted, requiring more effort to maintain balance and increasing the risk of falls or discomfort. In landscape design, the slope, surface material, and width of pathways can either facilitate or hinder smooth, natural movement patterns, making it crucial to design spaces that accommodate proper gait.

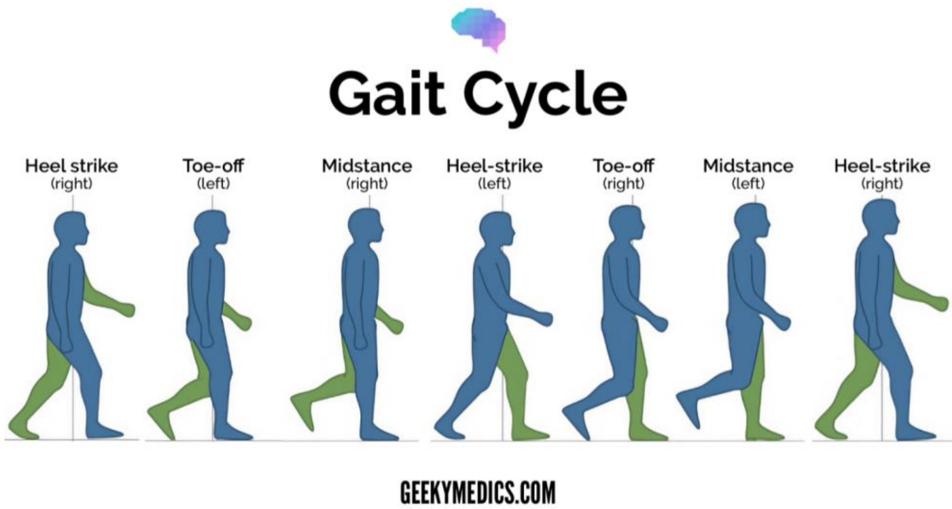

Figure 5. Gait cycle [23].

A crucial aspect of gait analysis is balance, which refers to the body's ability to maintain stability during movement or while reacting to external forces. Balance involves coordinating sensory input from the body with muscular and skeletal actions to keep the center of mass aligned over the base of support. Maintaining balance is vital for preventing falls, reducing strain, and ensuring smooth transitions between steps during walking or running. Balance can be compromised in environments with poor design—such as narrow or uneven walkways, slippery surfaces, or cluttered interiors. Individuals may have to compensate by adjusting their gait, which can lead to fatigue or discomfort over time. For example, a narrow hallway might force someone to take shorter, more cautious steps, interrupting their natural stride and placing additional stress on muscles and joints.

In contrast, spaces that account for the natural gait cycle and support balance promote fluid, efficient movement. Wide pathways, slip-resistant surfaces, and lighting can all enhance gait by creating an environment where individuals feel secure and can move freely without fear of stumbling or fatigue. Whether in interior spaces like offices or exterior spaces like parks, considering gait and balance in design can significantly improve comfort, safety, and overall user experience. By integrating an understanding of gait into design, spaces can be tailored to support natural human movement, reduce injury risks, and enhance the ease with which people navigate their environments. This is especially important in spaces where frequent walking or running occurs, such as pedestrian walkways, exercise areas, or workspaces that require mobility.

2.2. SD: Interior and landscape perspectives

Spatial arrangements in design, whether in interior or landscape contexts, involve the strategic organization of physical elements to optimize functionality and aesthetics. The objective is to create environments that meet practical needs and foster comfort, movement efficiency, and a positive sensory experience. In interior and landscape design, the relationship between space and the HBD is central to determining these arrangements' effectiveness. Understanding how people move, rest, and interact with their surroundings is crucial for creating spaces that enhance usability and satisfaction.

In interior design, spatial arrangement involves carefully placing furniture, fixtures, and architectural elements to create functional and comfortable environments. Key considerations include the flow of movement, ergonomics, and balance. For example, in a living room, furniture arrangement should promote easy interaction, clear lines of sight, and unobstructed pathways that facilitate natural movement between spaces. Similarly, ergonomically designed office layouts enhance productivity in work environments by ensuring that desks, chairs, and equipment are positioned to minimize strain and support proper posture. **Figure 6**, highlights how male and female body dimensions influence seating requirements, illustrating the need for ergonomic design [24]. **Figure 7** shows how the dimensions of sofas and circulation spaces must account for body size to ensure comfort and functionality, especially in seating arrangements.

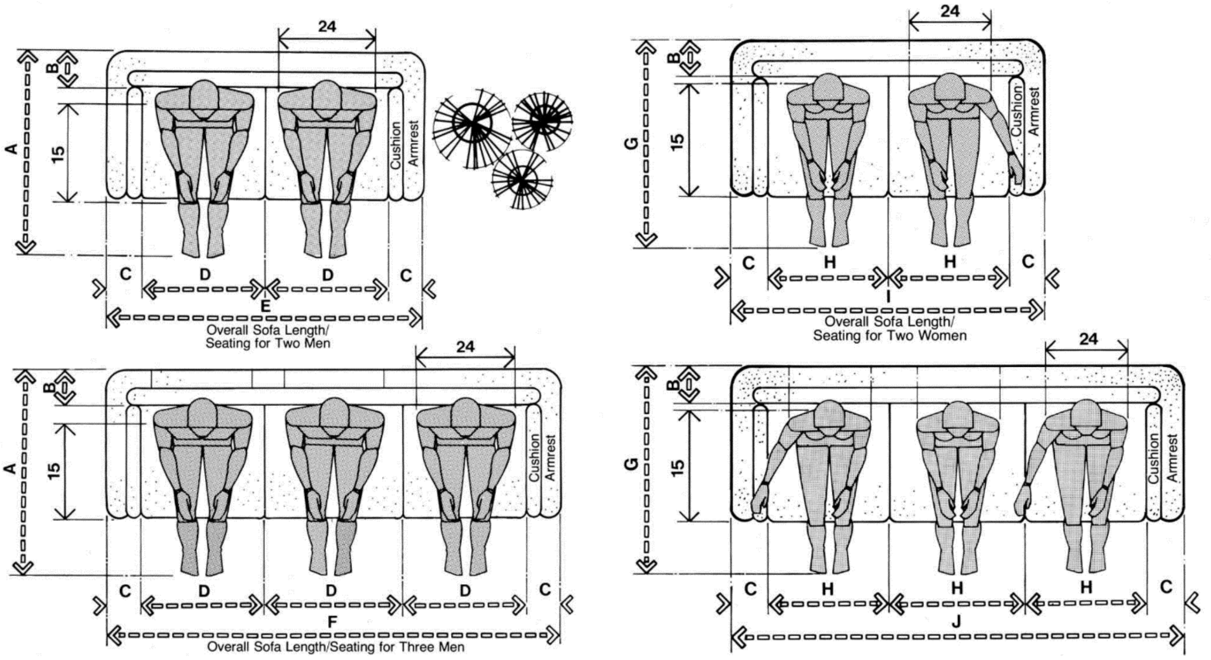

Figure 6. Male and Female body dimensions for seating requirements [24].

Practical interior spatial arrangements are also influenced by zoning, which organizes spaces according to their intended function. For example, in open-plan interiors, distinct zones might be created for activities such as relaxation, dining, or working, with each area designed to meet the specific needs of those activities.

Circulation pathways between zones are equally important, allowing seamless movement and reducing congestion or obstruction. In residential spaces, for example, hallways, doorways, and stairs must be wide enough and properly positioned to facilitate safe and comfortable transitions between rooms.

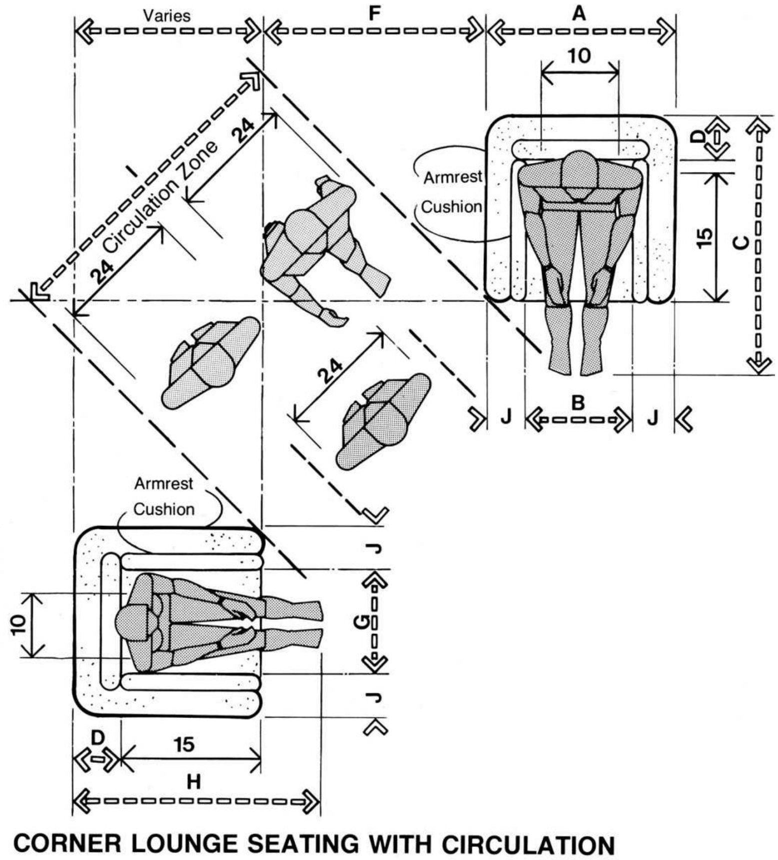

Figure 7. Sofas and circulation spaces to ensure comfort and functionality [24].

Scale and proportion are also crucial to spatial arrangements. Spaces must be designed considering the human body's dimensions and range of movement. For instance, too low ceilings or disproportionately large furniture can make a space feel cramped and uncomfortable. On the other hand, overly large spaces without adequate furniture or objects can feel empty and disorienting. Designers must balance these factors to ensure the space feels proportionate and human-centered. In landscape design, spatial arrangement extends beyond the indoor environment and encompasses outdoor spaces such as parks, gardens, and public plazas. Landscape design considers the aesthetic placement of plants, walkways, and structures and how these elements interact with people's natural movement patterns. The goal is to create spaces that are inviting, functional, and aligned with the natural surroundings.

Key considerations in landscape spatial arrangements include pathway design, terrain, and vegetation placement. Pathways must be thoughtfully designed to accommodate foot traffic, considering aspects like width, surface material, and slope. Well-designed pathways should promote efficient movement while guiding users through the space naturally and intuitively. For instance, in a public park, pathways should connect key areas, such as playgrounds or seating areas, while avoiding unnecessary detours or abrupt changes in direction. In addition, terrain and topography are integral to landscape SD. Designers must account for natural slopes, elevation changes, and water drainage to ensure that outdoor spaces are aesthetically pleasing and functional. This may involve the creation of terraces, ramps, or stairs to navigate hilly areas or using retaining walls to manage uneven terrain. Proper terrain management is also essential for preventing soil erosion and ensuring the durability of pathways and structures.

Vegetation is another critical element of landscape spatial arrangements. Trees, shrubs, and plants often define spaces, create visual interest, and provide shade or shelter. The placement of vegetation can also influence movement patterns, as certain plants may be used to create borders or guide pathways. Furthermore, vegetation plays a significant role in the sensory experience of a space, offering texture, color, and fragrance that enhance the overall ambiance. Both interior and landscape design aim to create cohesive, functional environments that accommodate human movement and promote well-being. The spatial arrangement of elements must be carefully considered to align with how people naturally move, interact, and experience their surroundings. Whether indoors or outdoors, a successful design integrates form and function, using space efficiently while enhancing the quality of the user experience. By understanding how the HBD interacts with space, designers can create environments that are visually appealing but also comfortable, practical, and accessible.

2.3. Relationship between movement and SD

The relationship between movement and SD is fundamental in creating environments that accommodate the natural flow of human activity. Movement, whether walking, sitting, or interacting with objects, shapes how people experience and navigate spaces. Understanding HBD, including movement patterns, in interior and landscape design is essential for creating functional, efficient, and aesthetically pleasing environments that enhance the user experience. Movement flow refers to the ease and efficiency individuals can move through a space. A well-designed environment should account for people's paths and how they transition between different areas. For instance, in an open-plan interior, the placement of furniture, fixtures, and architectural elements must consider how people will walk from one room to another, navigate around objects, or shift between standing and sitting positions. Poor SD can create obstacles or bottlenecks, making movement awkward and uncomfortable, whereas well-planned spaces promote smooth and intuitive navigation.

In interior spaces, movement is guided by how rooms are laid out and how objects within those rooms are arranged. For example, in a kitchen, the layout of appliances and work surfaces should allow for efficient movement during cooking activities, minimizing the need to walk long distances between the stove, sink, and refrigerator. Similarly, furniture should be positioned in living rooms or offices to support social interaction and ease of movement, allowing individuals to transition between activities—such as conversing, working, or relaxing—without disruption. Ergonomics is critical in ensuring that movement within a space is comfortable and efficient. Spaces designed with ergonomics in mind consider the natural posture and movement of the HBD, minimizing physical strain during everyday activities. For example, the height of work surfaces, the depth and angle of chairs, and the reach required to access frequently used objects influence how comfortable and efficient movement is within a space. If these elements are misaligned with HBD, users may experience discomfort or fatigue, particularly over extended periods of use.

Movement is also critical in landscape design, particularly in outdoor spaces like parks, plazas, or walking paths. The design of these spaces must account for how people will move through them, whether walking, jogging, or cycling. Pathways should be wide enough to accommodate multiple users, and they should be designed with gentle curves or straight lines that facilitate easy movement from one area to another. Abrupt changes in direction, uneven surfaces, or overly narrow pathways can impede movement and lead to discomfort or injury. In addition to accommodating practical movement needs, landscape design also considers how movement interacts with the sensory experience of the environment. For instance, the layout of a garden or public park might encourage users to take meandering paths that offer changing views of plants, water features, or sculptures, enhancing the aesthetic experience of moving through the space. The surface materials used in these areas—such as gravel, wood, or grass—can also influence the physical experience of walking, as different textures and softness underfoot affect how comfortable movement feels.

One key concept in the relationship between movement and SD is circulation—the organized flow of movement within a space. Circulation patterns help guide how people move from one area to another, whether in a building or an outdoor space. In public spaces like shopping malls, airports, or parks, circulation pathways are crucial for managing large numbers of people, preventing congestion, and ensuring users can navigate easily. In residential spaces, circulation patterns influence how people move between rooms and interact with their living environment daily. Finally, transition spaces—such as hallways, corridors, and doorways—are vital in facilitating smooth movement between different areas of a design. These spaces act as connectors, allowing individuals to flow naturally from one room or zone to another without abrupt stops or turns. In interior and exterior settings, transition spaces should be wide enough to accommodate traffic while providing visual cues that guide users in the direction they need to go.

3. HBD analysis

3.1. Methods for analyzing BM in design contexts

Analyzing BM within the design context is crucial for ensuring that spaces accommodate natural human motion and reduce the risk of strain or discomfort. Several biomechanical and ergonomic methods have been developed to study how the human body interacts with its environment. These methods provide valuable data for optimizing spatial arrangements in both interior and landscape design. The most common methods used to analyze BM in design contexts include gait analysis, motion capture, force plate analysis, and ergonomic assessment tools.

3.1.1. Gait analysis

Gait analysis involves the systematic study of human walking or running patterns. It examines various gait cycle phases, such as heel strike, mid-stance, and toe-off, to evaluate how the BM goes through space. Key parameters measured in gait analysis include stride length, speed, and ground reaction forces. In design, gait analysis is particularly useful for understanding how people navigate different surfaces, pathways, and environments. For example, in landscape design, gait analysis can help determine the appropriate slope or surface texture for walkways, ensuring that users can move comfortably and safely. In interior design, gait analysis can assess how individuals move between rooms or interact with obstacles like stairs, ramps, or door thresholds. The insights gained from gait analysis can guide the design of spaces that promote efficient and comfortable movement while reducing the risk of falls or fatigue. Gait analysis can be conducted using pressure-sensitive walkways or wearable sensors that track foot placement and movement patterns. These tools allow designers to gather data on how people's feet interact with surfaces, which is especially important in environments where slip resistance or uneven terrain might pose a challenge.

3.1.2. Motion capture systems

Motion capture (mocap) is a highly effective method for analyzing human BM in static and dynamic scenarios (**Figure 8**). By using specialized cameras and reflective markers placed on key points of the body (such as joints), motion capture systems can record the precise movements of individuals as they walk, sit, bend, or perform other activities. The data captured provides a detailed 3D model of the BM, allowing for an in-depth analysis of posture, joint angles, and movement efficiency. In interior design, motion capture can evaluate how people interact with furniture and objects, ensuring that seating arrangements or workstations support proper posture and movement. For instance, by studying how individuals sit down, rise, or reach for objects in a simulated environment, designers can adjust the height, depth, and orientation of chairs, desks, and shelves to minimize physical strain. In landscape design, motion capture can be applied to analyze how people walk on different terrains or navigate complex outdoor environments, such as steps, ramps, or inclines. This information can help design spaces catering to diverse user needs, ensuring accessibility for individuals with varying mobility levels. Motion capture technology has advanced significantly, with markerless systems now available, which use cameras and artificial intelligence to analyze movement without physical markers. This makes the process more convenient and less invasive, allowing for a more natural representation of human movement.

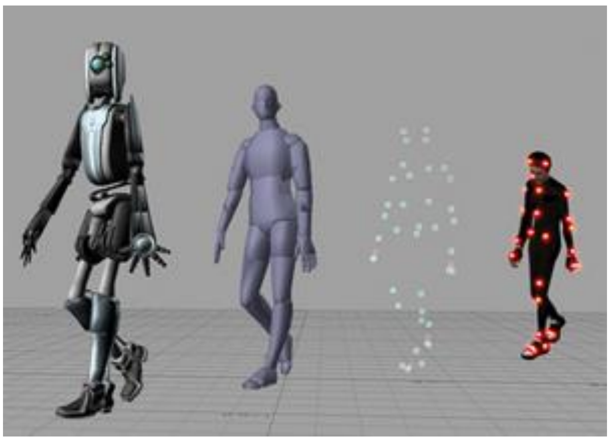

Figure 8. Motion capture.

3.1.3. Force plate analysis

Force plates measure the ground reaction forces generated when a person walks, stands, or performs other activities (**Figure 9**). These forces provide insights into how the body's weight is distributed and how individuals adjust their movements in response to different surfaces or inclines. Force plate analysis can identify imbalances in posture or movement that may lead to discomfort or injury. In a design context, force plates evaluate how flooring materials, surface inclines, or seating structures affect human movement. For example, force plates can help determine whether a particular surface creates too much impact during walking, potentially leading to joint strain or fatigue. Force plate analysis can guide decisions about anti-fatigue flooring or ergonomically optimized seating in offices or work environments. Additionally, in landscape design, force plate data can be used to assess how varying terrain, such as gravel paths or grassy areas, influences the forces acting during BM. This data helps landscape designers make informed choices about pathway materials and inclines that reduce physical strain for users.

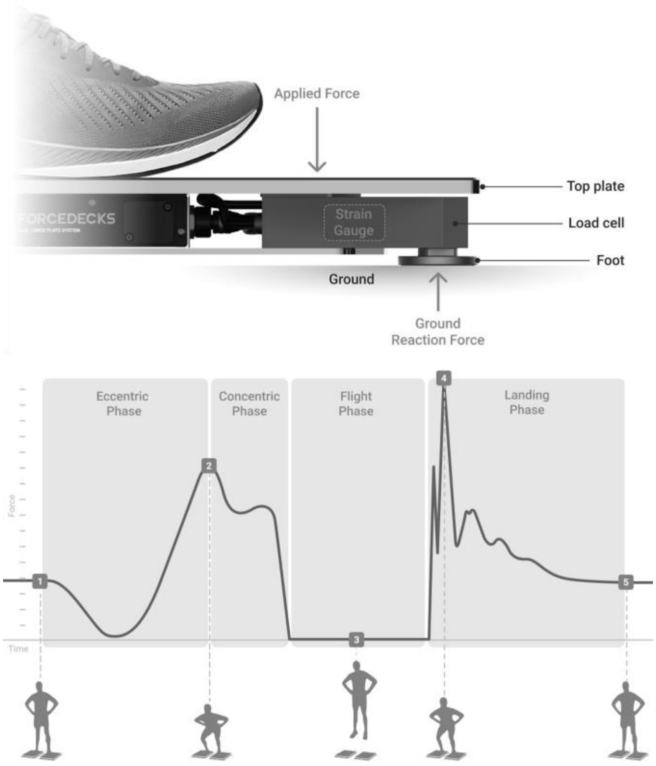

Figure 9. Force-time curve for a joint force plate test [25].

3.1.4. Ergonomic assessment tools

Ergonomic assessment methods evaluate how well a space or design supports human posture, comfort, and efficiency. Tools like the Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA) (**Figure 10**), and OWAS (Ovako Working Posture Assessment System) are commonly used in workplace design to evaluate the physical demands placed on the body during various tasks. In interior design, these tools are handy for assessing how well furniture and workspaces accommodate natural human movements. For example, when designing an office, an ergonomic assessment might look at how desk height, chair support, and monitor placement influence posture and movement throughout the workday. By using ergonomic tools, designers can make data-driven decisions that optimize the comfort and well-being of users. Ergonomic assessment tools can also be applied in landscape design, particularly in public spaces where individuals engage in prolonged standing, walking, or recreational activities. These tools help ensure that benches, seating areas, and pathways are designed to minimize discomfort and support diverse user needs.

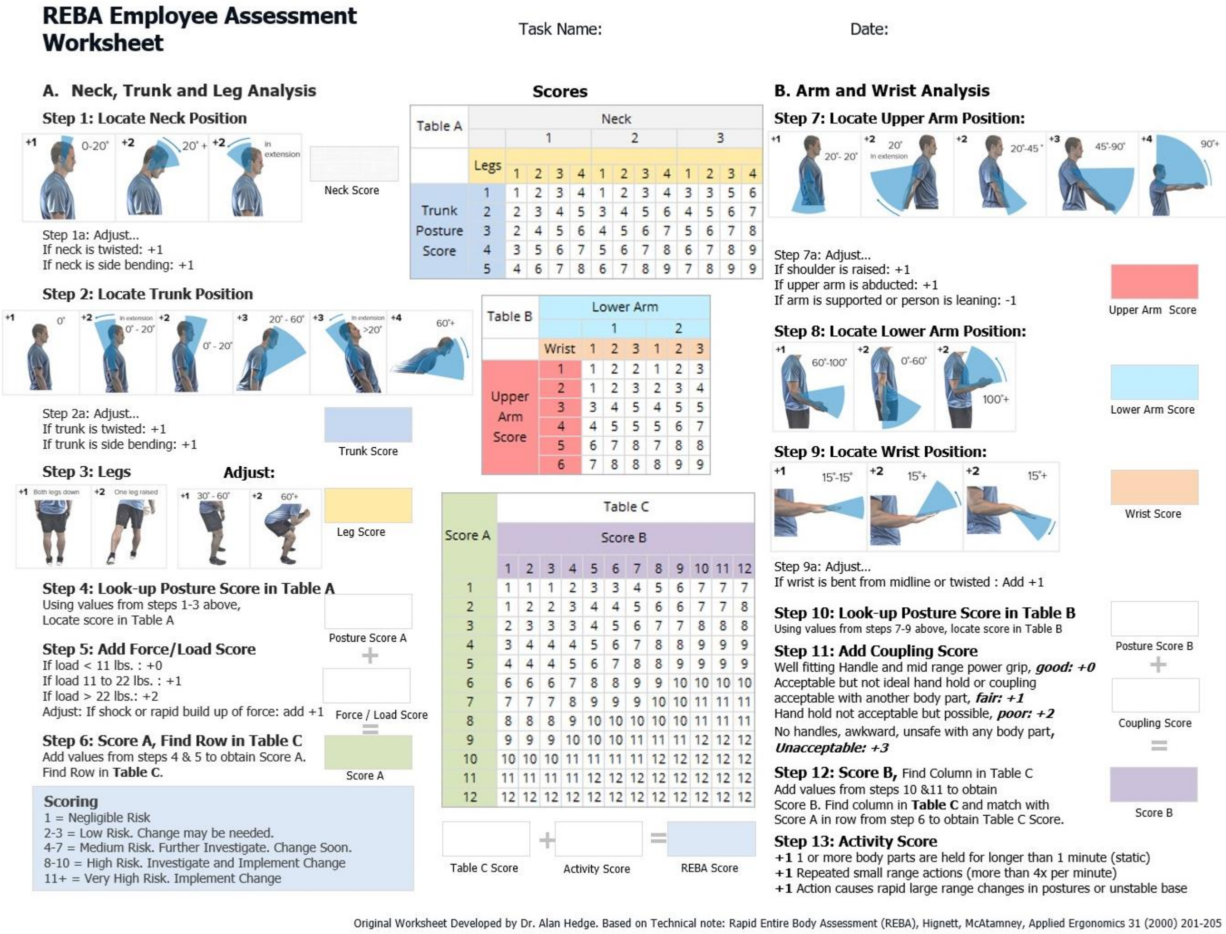

Figure 10. Rapid Entire Body Assessment (REBA) [26].

3.1.5. Wearable sensors and biomechanical models

Wearable sensors increasingly collect real-time data on BM and forces. These sensors, which can be placed on the skin or embedded in clothing, track key metrics such as joint angles, muscle activity (using electromyography), and BM (**Figure 11**). This data can then be analyzed to create detailed biomechanical movement models, giving designers a rich understanding of how the BM works with different spaces and surfaces. Biomechanical models are beneficial for simulating how different design elements—such as seat height, desk placement, or pathway slope—affect the body over time. For instance, a model might predict how long-term use of a particular chair will affect the spine or how walking on an incline influences joint stress. By combining data from wearable sensors with advanced computational models, designers can evaluate the long-term impacts of their spatial arrangements, ensuring that spaces not only support immediate comfort but also promote long-term well-being.

Figure 11. Wearable sensors [27–30].

3.2. Key parameters of human movement in SD

In SD, understanding the key parameters of human movement is essential for creating functional, comfortable, and efficient environments. These parameters offer critical insights into how individuals move, interact with objects, and navigate through spaces. By considering factors such as range of motion, speed, balance, reaction to external forces, and ergonomics, designers can optimize interior and landscape environments to accommodate natural human movements and ensure that spaces are tailored to user needs [31–35].

3.2.1. Range of motion

Range of motion refers to the full movement potential of a joint, typically measured in degrees of flexibility. It is a fundamental consideration in SD because it determines how much space individuals need to comfortably move their arms, legs, or body without restriction. For example [36–42], the design of seating areas, doorways, and workstations should consider the natural range of motion of the shoulders, elbows, knees, and hips. In interior design, range of motion is critical when designing spaces that involve repetitive tasks, such as kitchens, offices, or bathrooms. For instance, the height of countertops, the placement of shelves, and the spacing between furniture must allow for a full range of motion during daily activities like reaching, bending, or stretching. Poorly designed spaces that restrict the range of motion can cause discomfort or injury due to repetitive strain. In landscape design, range of motion is also essential when considering activities such as walking, exercising, or sitting in outdoor areas. Pathways, seating arrangements, and recreational spaces must provide enough room for natural BM, ensuring users can engage in activities without feeling confined or restricted.

3.2.2. Speed of movement

Speed of movement refers to how quickly individuals move through space, whether walking, running, or performing specific tasks. Space design must consider the speed at which people move through different areas. For instance, in high-traffic environments such as airports, shopping malls, or public parks, pathways must be wide enough to accommodate fast-moving and slower pedestrians without causing congestion. In interior spaces, movement speed is essential when designing circulation zones, such as hallways, stairways, and entryways. Faster movement requires wider paths and fewer obstacles, while slower, more deliberate movements may allow for narrower or more segmented spaces. For example, in office settings, movement between workstations and meeting rooms should be streamlined to avoid unnecessary delays while providing enough space for employees to move comfortably without bumping into furniture or colleagues. In landscape design, the speed of movement influences the design of pathways, trails, and recreational areas. Spaces intended for activities such as jogging or cycling require more extended, more linear pathways with gentle curves, while areas for strolling or resting may incorporate meandering paths or seating that encourages slower, more leisurely movement. Designers must also account for the varying speeds of different user groups, such as children, elderly individuals, or people with disabilities, ensuring that spaces are accessible and safe for all.

3.2.3. Balance and stability

Balance is the body's ability to maintain stability during movement or while standing still, and it plays a crucial role in SD. Spaces must support balance by providing even, stable, and supportive surfaces. Poor balance, caused by uneven surfaces or awkward transitions between levels, can lead to falls, discomfort, or injury. In interior design, the balance and stability of users are influenced by the flooring materials, staircase design, and furniture height. Slippery or uneven floors can disrupt balance, especially for older individuals or those with mobility issues. Therefore, designers must select materials that offer sufficient traction and ensure smooth transitions between surfaces (such as carpet to tile or flooring to stairs). In seating arrangements, chairs, and sofas should be stable, with armrests or back supports that help individuals maintain balance when sitting down or standing up. In landscape design, balance is essential when considering the terrain and surface materials of pathways, parks, or recreational spaces. Inclines, declines, and uneven surfaces (gravel or cobblestones) can affect the body's stability. Therefore, designers must assess the steepness of paths and ensure that walking surfaces provide enough support and grip for safe movement. In public parks or plazas, for instance, including handrails or guardrails on steps or slopes can improve balance and reduce the risk of accidents.

3.2.4. Reaction to external forces

External forces, such as gravity, friction, and resistance from objects or surfaces, constantly influence human movement. Designers must consider how these forces affect movement within a space, ensuring that individuals can move efficiently and safely without unnecessary strain or resistance. In interior design, reaction to external forces is critical when selecting flooring materials, arranging furniture, or designing elements like stairs or ramps. For example, materials with high friction (such as rubber or textured surfaces) can provide better grip and stability, reducing the risk of slipping. On the other hand, smooth surfaces, like polished wood or marble, may increase the likelihood of falls unless appropriately designed with anti-slip treatments or mats. Designers should also consider the ease with which objects can be moved or adjusted within a space, ensuring that chairs, tables, or equipment can be rearranged without excessive effort or resistance. In landscape design, external forces such as wind, rain, or uneven terrain can affect how people move through outdoor spaces. Pathways and seating areas must be designed to withstand environmental forces, with materials and slopes that promote drainage and prevent pooling water. Additionally, outdoor furniture should be stable and resistant to environmental factors like strong winds, ensuring that users can move through the space safely, even during adverse weather conditions.

3.2.5. Posture and ergonomics

Posture is a key factor in how comfortably and efficiently individuals move through a space. Ergonomically designed environments promote healthy posture by aligning the body to reduce strain on muscles, joints, and bones. Poor posture caused by awkward spatial arrangements can lead to discomfort, fatigue, or long-term injury. In interior design, ergonomics is vital in optimizing furniture placement, workstations, and seating arrangements. For example, in office environments, the height and angle of desks, chairs, and computer monitors must be carefully calculated to support proper posture. In kitchens, the height of countertops and the reach required to access shelves or appliances must allow for a natural and comfortable posture to prevent back or neck strain. In living spaces, seating should support the spine's natural curvature and allow for relaxed positioning of the legs and arms. In landscape design, posture, and ergonomics are considered when designing benches, picnic areas, or outdoor workspaces. Seating in parks or public spaces should be positioned to support the body's natural alignment, allowing users to sit comfortably without slouching or overextending their limbs. Additionally, outdoor workstations, such as gardening areas or play equipment, should accommodate various body types and activity levels, ensuring that individuals can engage with the space comfortably and safely.

3.2.6. Coordination and timing

Coordination is performing movements smoothly and efficiently by synchronizing different body parts. In SD, spaces must be arranged to promote coordination, ensuring that users can interact with multiple elements of the environment without unnecessary effort or confusion. Timing, on the other hand, refers to how quickly and accurately individuals can perform tasks or movements within a space. Both coordination and timing are crucial for ensuring that spaces are intuitive and easy to navigate. In interior design, coordination and timing are essential when considering how individuals interact with multiple objects or devices in a space. For example, in a kitchen, the arrangement of appliances, storage areas, and work surfaces must allow for seamless transitions between tasks, such as chopping vegetables, cooking, and washing dishes. In offices or workspaces, equipment and tools should be positioned within easy reach, allowing for smooth coordination of tasks and reducing the time and effort required to complete activities. In landscape design, coordination, and timing are essential for users engaging in recreational activities, such as running, cycling, or playing sports. Pathways, exercise stations, and recreational areas should be designed to promote natural, rhythmic movements that are easy to coordinate. Timing is essential in high-traffic areas, such as pedestrian walkways or bike paths, where smooth, efficient movement reduces the risk of collisions or congestion.

3.3. Case studies: Analyzing HBD in existing spaces

HBD has been central to designing innovative and functional spaces where human movement and environmental interaction are key factors. These case studies demonstrate how understanding and applying principles of HBD can lead to optimized designs that enhance comfort, efficiency, and safety. Here are several examples that illustrate the application of HBD in both interior and landscape design:

3.3.1. Case study 1: Ergonomically designed office spaces (Google headquarters, California)

One of the most well-known examples of HBD applied in interior design is at Google's headquarters in California (**Figure 12**). Google's approach to workplace design focuses heavily on ergonomics and movement flow to enhance employee productivity, well-being, and comfort. The workspaces are created with adjustable height desks, ergonomic chairs, and task-specific furniture that promotes natural BM and minimizes strain. In these office spaces, designers considered the range of motion for various tasks. Employees can switch between sitting and standing positions without compromising posture, and workstations are arranged so that monitors, keyboards, and desks are positioned to reduce repetitive strain injuries, such as neck or wrist discomfort.

Moreover, seating arrangements and paths between desks and meeting rooms are designed to facilitate efficient movement flow, ensuring that people can move through the space without bumping into objects or disturbing others. Additionally, Google's design integrates motion capture analysis during planning to ensure that seating, desk height, and spatial arrangement accommodate natural BM. This approach has increased worker satisfaction and productivity, as employees experience less physical fatigue and more comfort during long work hours.

Figure 12. Google headquarters, California.

3.3.2. Case study 2: Universal design in public transportation (Stockholm Metro, Sweden)

The Stockholm Metro (**Figure 13**) is an excellent example of how HBD has been applied in public infrastructure design, focusing on accessibility and movement for all individuals, regardless of age or physical ability. The station designs consider the HBD of diverse users, including older adults, people with disabilities, and families with children. By conducting gait and force plate analysis, designers ensured that walking surfaces were slip-resistant and appropriately sloped for easy movement. The ramps and staircases are engineered to maintain balance and stability, reducing the risk of trips or falls. Additionally, seating areas are ergonomically designed with proper back support and height-adjustable seating for individuals of different sizes and physical abilities. The metro stations feature wide circulation pathways that account for the speed of movement of various users. For example, escalators are positioned at different intervals, and walking paths are wide enough to accommodate fast-moving commuters while providing sufficient space for those who need to move more slowly, such as parents with strollers or individuals with mobility aids. This design optimizes movement flow and ensures all users' safety and comfort, reflecting universal design principles.

Figure 13. Stockholm Metro.

3.3.3. Case study 3: Outdoor Park design for gait and movement (High Line, New York City)

The High Line Park in New York City (**Figure 14**) exemplifies how HBD can shape landscape design to enhance user experience. Originally an elevated railway track, the High Line was transformed into a public park that stretches across several blocks of Manhattan. Designers used gait analysis to assess how visitors would move through the park and interact with its features. The pathways are wide and smooth, with gradual curves that align with natural walking patterns. This reduces the need for abrupt changes in direction, promoting efficient and comfortable movement. The materials used for the paths—such as concrete and permeable pavers—were chosen for their durability and ability to provide a stable walking surface that maintains balance in all weather conditions. The park also integrates seating zones with ergonomically designed benches that consider visitors' posture and range of motion. These seating areas are placed strategically to encourage people to pause, relax, and enjoy the surrounding views without straining their bodies. The designers carefully considered how people would transition from walking to sitting and provided accessible seating options for elderly and physically challenged visitors. This attention to HBD has made the High Line a popular destination for locals and tourists, who appreciate its comfort and ease of use.

Figure 14. High Line Park, New York City.

3.3.4. Case study 4: Airport terminal design for movement flow (Changi Airport, Singapore)

Changi Airport in Singapore (**Figure 15**) is renowned for its efficient design, which integrates HBD principles to optimize movement flow through its terminals. One of the airport's key design goals was to create a space that allows passengers to navigate seamlessly between check-in counters, security areas, boarding gates, and retail zones without experiencing physical discomfort or disorientation. Designers used motion capture systems to model how passengers would move through the space, paying particular attention to the speed of movement and coordination required for transitions between tasks, such as moving from security checks to baggage claim areas. Based on this data, they optimized circulation zones, ensuring pathways were wide enough to handle peak-hour traffic without causing congestion. Moving walkways and elevators are positioned to reduce the physical effort required to move between different terminal levels, particularly for passengers carrying luggage or traveling with children. The terminal also features ergonomic seating in waiting areas, with chairs and lounge spaces designed to support natural BM during long periods of sitting. This focus on HBD ensures that passengers experience minimal fatigue while waiting for flights, and the intuitive layout of the terminal reduces stress and confusion, making the travel experience more pleasant.

Figure 15. Changi Airport, Singapore.

3.3.5. Case study 5: Residential design for aging populations (The ARC, London)

The ARC, a senior living facility in London (**Figure 16**), was explicitly designed to accommodate the HBD of aging populations. The designers conducted extensive studies on posture, range of motion, and balance to create an environment that supports the physical and ergonomic needs of elderly residents. The layout of the residential units ensures that all furniture, appliances, and fixtures are placed at accessible heights, reducing the need for bending or stretching, which can strain aging joints. For example, kitchen countertops, cupboards, and storage areas are all within easy reach, while seating areas feature high-back chairs with armrests supporting natural sitting and standing motions. In addition, balance was a key consideration in the design of the facility’s walking paths and common areas. Floors are constructed from materials that provide sufficient traction, minimizing the risk of slips and falls. Handrails are strategically placed along corridors and staircases, and transitions between different levels use gentle ramps rather than steep steps. The ARC also features exercise zones where residents can engage in physical activity designed to improve mobility and balance, further enhancing their ability to navigate the space safely.

Figure 16. The ARC, London.

4. Application to interior design

4.1. Optimizing furniture layout

Furniture layout shapes how individuals move and interact within a space. To create ergonomic environments that support natural human movement, it is essential to consider movement patterns, BM, and functional needs when arranging furniture. The goal is to align the layout with how people naturally walk, sit, stand, and transition between activities, ensuring that movement is fluid, efficient, and free from unnecessary strain or discomfort.

4.1.1. Human movement patterns and ergonomic design

Human movement patterns—whether walking, bending, sitting or reaching—inform the optimal furniture arrangement in residential and commercial settings. Ergonomically arranged furniture allows for natural and comfortable BM, minimizing the risk of repetitive strain or injury. For example, seating should be arranged in a living room to allow people to stand up and sit without excessive effort. Furniture pieces such as sofas, chairs, and coffee tables should be placed at appropriate distances from each other, ensuring that users can walk between them without bumping into obstacles. In office environments, optimizing furniture layout is particularly important for enhancing productivity and reducing physical discomfort. Desks, chairs, and monitors should be positioned to support a neutral posture where the body is aligned in its most natural position. This involves placing computer monitors at eye level to prevent neck strain, adjusting chair height so that feet rest flat on the floor, and arranging workstations to reduce the need for excessive reaching or bending.

Moreover, furniture like adjustable standing desks allows users to switch between sitting and standing positions throughout the day, further promoting movement and reducing the risk of musculoskeletal issues. Furniture layout should account for individual comfort and group interactions in public spaces such as restaurants, libraries, or waiting areas. For instance, seating in a restaurant should be spaced to allow for ease of movement between tables while still promoting social interaction. In waiting areas, seating should be placed to facilitate movement without creating congestion while ensuring individuals have enough personal space to feel comfortable.

4.1.2. Principles of spatial efficiency in furniture layout

An optimized furniture layout considers clear circulation paths that allow people to move smoothly between different room areas. In residential spaces, this means creating direct paths between commonly used zones, such as from the living room to the kitchen or from the bedroom to the bathroom. In commercial environments, clear circulation paths ensure employees can move freely between workstations, meeting rooms, and common areas. In addition to circulation paths, the scale and proportion of furniture should align with the dimensions of the room and the people who will use it. Oversized furniture in small spaces can restrict movement, while undersized furniture in large spaces can make the room feel empty and disconnected. Ergonomic design principles encourage furniture that fits comfortably within the space while allowing for free movement and flexibility. Modular furniture offers another solution for optimizing layout, as it can be rearranged to meet different functional needs or accommodate varying numbers of users. Modular furniture can be easily reconfigured in conference rooms or co-working environments to support collaboration, presentation, or relaxation, depending on the activity.

4.2. Movement flow and circulation

The flow of movement within a space is a key element of SD, as it directly influences how users navigate, interact, and experience their environment. Efficient circulation design optimizes ease of movement, accessibility, and safety, ensuring spaces feel open and intuitive. In interior and exterior spaces, movement flow is about creating pathways and circulation zones that allow individuals to move freely without encountering obstacles or feeling crowded.

4.2.1. Designing for movement efficiency

Designing for movement efficiency begins with understanding human walking patterns and how people typically move through different environments. In interior spaces, movement flow is dictated by the placement of entryways, furniture, and architectural elements such as walls or partitions. For example, workstations should be arranged in an open-plan office to allow employees to move between desks, meeting rooms, and common areas without crossing high-traffic zones or encountering bottlenecks. In residential design, circulation must be planned for easy transitions between rooms. Hallways should be wide enough to accommodate foot traffic, and doorways should be strategically placed to facilitate smooth movement between spaces. For example, in a home, the movement flow from the kitchen to the dining room should be direct and unobstructed, allowing individuals to move freely while carrying items such as dishes or food. In public and commercial spaces, movement flow often involves managing large numbers of people, which requires careful planning to prevent congestion. For instance, circulation pathways must be wide enough to handle heavy foot traffic in airports, shopping malls, or hotels during peak times. Wayfinding elements such as signage, lighting, and floor markings can guide users through the space, ensuring they know where to go without stopping and searching for directions.

4.2.2. Optimizing circulation zones

Circulation zones are the areas within a space that facilitate movement between different functional areas. For example, the space between workstations and communal areas, such as kitchens or restrooms, is a critical circulation zone in an office. These zones must be wide enough to accommodate walking and activities like carrying objects, maneuvering through doors, or interacting with others. In landscape design, pathways and walkways serve as the primary circulation zones. Well-designed pathways should allow for smooth transitions between different areas of a park or garden, connecting key features such as seating areas, fountains, or playgrounds. The slope, width, and surface material of walkways must be carefully considered to ensure that movement is easy, safe, and accessible for all users, including those with disabilities or limited mobility. Vertical circulation, including stairs, ramps, and elevators, is another important aspect of movement flow. Stairs should have an appropriate rise and run to ensure safety, while ramps should comply with accessibility standards to accommodate wheelchair users or those with mobility challenges. Elevators should be conveniently located to ensure individuals can move between floors without unnecessary detours.

4.3. Impact of surface materials and spatial experience

The selection of surface materials significantly influences a space’s physical comfort and aesthetic experience. Materials like wood, concrete, tile, or carpet can alter how a space feels, how people interact, and even how people move within it. When designing interior or landscape spaces, it’s essential to consider how materials’ texture, temperature, and durability will affect users’ experience.

In interior design, choosing a flooring material can impact comfort and movement. For example, hard materials like tile or stone may be visually appealing and easy to clean, but they may also cause discomfort during long periods of standing or walking, especially in areas such as kitchens or offices. Soft materials like carpet or cork can provide cushioning, reducing the impact on joints and making movement more comfortable. However, soft materials may also introduce friction, slow movement, or create challenges for individuals with mobility aids such as wheelchairs. Surface materials also affect the acoustic quality of a space, contributing to the overall sensory experience. Hard surfaces like wood or tile tend to reflect sound, which may amplify noise in high-traffic areas, while softer surfaces like carpet or fabric absorb sound, creating a quieter and more intimate atmosphere. In workspaces or public buildings, the acoustic properties of surface materials should be carefully considered to ensure that noise levels do not interfere with concentration or conversation.

In landscape design, surface materials are critical for both practicality and comfort. For example, gravel paths may create a rustic aesthetic but can be challenging to walk on for people with mobility impairments or those using strollers or wheelchairs. In contrast, concrete or asphalt pathways offer a smooth and durable surface that supports ease of movement for a wider range of users. Surface materials also influence traction and slip resistance, crucial for ensuring safety in outdoor environments, particularly in areas prone to rain or snow. Surface materials can also affect the thermal experience of a space. In outdoor environments, materials like stone or concrete absorb heat, making them uncomfortable to walk on during hot weather, whereas grass, wood, or permeable pavers may remain more relaxed and pleasant underfoot. In interior spaces, the temperature of materials like metal or glass can influence how comfortable it is to touch them, which is particularly important in high-traffic areas or spaces where people frequently interact with surfaces.

From an aesthetic perspective, the choice of surface materials plays a key role in shaping a space's overall feel and appearance. The materials' color, texture, and pattern evoke different emotions and experiences. For instance, natural materials like wood and stone often create a warm and inviting atmosphere, while sleek materials like glass or metal can lend a modern, minimalist aesthetic. By combining different materials strategically, designers can create visually dynamic and physically comfortable spaces.

5. Application to landscape design

5.1. Human movement in outdoor spaces

Human movement in outdoor spaces, such as parks, plazas, and recreational areas, plays a significant role in shaping the design of these environments. Outdoor spaces should be planned with an understanding of how people move through them, ensuring that pathways, recreational zones, and open areas support natural and efficient BM. Designers must consider the need for active and passive spaces, allowing for various activities such as walking, running, resting, and playing. Walking paths are essential for guiding movement through outdoor spaces. They should be wide enough to accommodate multiple users, such as pedestrians, joggers, and cyclists, and should be free of obstacles that disrupt movement. The alignment of pathways should also allow for smooth transitions between areas of different use, such as recreational fields, seating areas, and playgrounds. For example, paths should curve gently or follow natural contours to avoid abrupt changes in direction, which can cause discomfort or confusion for users. Recreational areas should encourage natural movements, providing ample space for activities that require a wide range of motion, such as sports or group exercises. These areas should also include sufficient space for people to move freely without the risk of collisions or overcrowding. Open spaces, such as lawns or plazas, provide flexibility for unstructured activities like picnicking or spontaneous play, further supporting various forms of movement. The design of outdoor spaces must also consider the diverse needs of different user groups, including children, older people, and individuals with disabilities. Paths should be accessible and barrier-free, with appropriate resting points like benches or shaded areas. By carefully considering human movement, outdoor spaces can become inclusive environments that enhance physical activity, social interaction, and overall well-being.

5.2. Influence of terrain and pathway design

The terrain and design of pathways profoundly impact HBD in outdoor landscapes. Terrain can vary significantly in outdoor spaces, from flat, easy-to-navigate areas to hilly or uneven ground requiring more effort. The design of pathways, including slope, width, and surface material, must account for these variations to ensure that movement is comfortable, safe, and accessible to all users. The slope of a pathway plays a critical role in determining how easily people can move through a space. Gentle slopes allow for more effortless movement, particularly for those with mobility challenges, such as elderly individuals or those using wheelchairs.

On the other hand, steeper slopes can increase the physical effort required, which may be suitable for recreational activities like hiking but can be challenging in urban or park settings where accessibility is a priority. To maintain comfort and safety, slopes should be gradual, and where steeper inclines are necessary, handrails or resting areas should be provided. Surface materials also influence HBD by affecting traction and stability. Materials like gravel, dirt, or cobblestone may create a rustic or natural aesthetic but can be challenging to navigate for individuals with mobility aids or those pushing strollers. In contrast, smooth materials like asphalt, concrete, or permeable pavers provide stable, slip-resistant surfaces that are easier to walk on, particularly in areas prone to rain or snow. Designers must carefully choose materials based on the intended use of the pathway, ensuring both aesthetic appeal and functionality. Pathway width is another crucial element that impacts movement flow. Narrow paths may restrict movement, making it difficult for people to pass each other or accommodate different types of traffic, such as walkers, cyclists, and runners. Wider paths, on the other hand, allow for smoother movement, reducing congestion and allowing different groups of users to navigate the space simultaneously. Pathways design should accommodate multiple lanes or provide dedicated paths for cyclists or runners in high-traffic areas to avoid conflict with pedestrians.

5.3. Interaction with natural elements

Natural elements such as trees, shrubs, and water features significantly influence outdoor movement and sensory experiences. The arrangement and placement of plants and natural features can guide how people move through a space, create focal points that encourage pauses or interactions, and enhance the overall atmosphere of the environment. Trees and shrubs are often used as natural barriers or borders that define walking paths, create privacy, or separate different activity zones. For example, a row of trees along a path can guide movement by visually directing people toward a specific destination. In public parks or recreational spaces, plantings can help delineate areas for specific activities, such as sports fields or quiet gardens, ensuring that movement between these areas is intuitive and fluid. Natural elements also contribute to the sensory experience of a space, enhancing the enjoyment and comfort of outdoor environments. Plants' texture, color, and fragrance create a dynamic and engaging experience that can influence how people feel as they move through the space. For example, walking through a shaded pathway lined with fragrant flowers or hearing the sound of a nearby water feature can make the space more inviting and relaxing, encouraging people to linger or take leisurely walks. Water features like fountains, ponds, or streams often become focal points in outdoor spaces, drawing people to them and creating gathering spots. The sight and sound of water can have a calming effect, slowing the pace of movement and encouraging people to pause, sit, or interact with the environment.

Similarly, variations in topography, such as small hills or dips in the landscape, can invite exploration, prompting individuals to take different routes or engage in spontaneous activities like climbing or running. Designers must balance aesthetics and functionality when incorporating natural elements into outdoor spaces. While natural features enhance a space's beauty and sensory richness, they should not impede movement or create hazards. For example, overgrown plants or poorly maintained landscapes can obstruct paths or reduce visibility, making navigation difficult and potentially unsafe. Thoughtful placement and maintenance of natural elements can create visually appealing environments that are easy to move through.

6. Design principles for optimizing spatial arrangements

6.1. Integration of biomechanics in design guidelines

Incorporating biomechanics into design guidelines requires understanding HBD, including posture, movement, and physical interaction with spaces. Designers can use these principles to create environments that enhance comfort, efficiency, and safety by aligning the design with natural body mechanics.

Here are key recommendations for integrating biomechanics into design guidelines:

(1) Consider range of motion: Design elements should accommodate the natural range of motion for various activities, such as sitting, standing, reaching, or walking. For instance, in kitchens, countertops should be at heights that allow comfortable reaching and bending, while seating in workspaces should allow individuals to maintain ergonomic posture without overextending their limbs. This ensures that users can interact with objects and spaces without strain.

(2) Use ergonomically optimized furniture: Furniture should be designed and positioned to promote proper BM and reduce stress on the musculoskeletal system. Chairs, desks, and tables should support a neutral posture, allowing the spine to maintain its natural curve and minimizing the risk of repetitive strain injuries. Adjustable furniture can accommodate users of different sizes and preferences.

(3) Analyze movement pathways: Pathways within both interior and exterior spaces should be wide enough to facilitate smooth movement without obstruction. Narrow corridors or poorly placed furniture can disrupt the natural flow of movement and cause discomfort or safety hazards. Clear and logical pathways reduce physical effort and ensure ease of navigation.

(4) Account for force and torque in design: Designs should minimize the forces and torques users must apply during everyday activities. For example, door handles and knobs should require minimal effort to turn, and chairs should provide proper

leverage for standing up quickly. Reducing physical exertion in these areas enhances comfort and accessibility.

(5) Optimize surfaces for movement and stability: The choice of surface materials should prioritize traction, stability, and ease of movement. In indoor and outdoor settings, surfaces should provide sufficient grip to reduce the risk of slipping while allowing for smooth, natural movements. Avoid surfaces that require excessive effort to navigate, especially for individuals with mobility challenges.

(6) Incorporate feedback loops: Designers should collect and incorporate user feedback to continually refine guidelines based on real-world use. Biomechanics-informed design should be an iterative process where user interaction data informs ongoing improvements in layout, furniture design, and space utilization.

6.2. Dynamic spatial zones for enhanced user interaction

Dynamic spatial zoning refers to the organization of space based on varying human activity levels, optimizing usability and interaction. By analyzing human movement patterns and activity levels in different areas, designers can create zones that cater to the specific needs of users, enhancing both the function and experience of a space.

(1) Activity-specific zones: Dynamic zoning should prioritize spaces based on the intended level of physical activity. High-activity zones, such as recreational or work areas, require ample space for movement, flexible furniture arrangements, and clear paths for circulation. Conversely, low-activity zones, such as relaxation areas or reading nooks, should offer comfortable seating and a calming atmosphere to encourage rest and reflection.

(2) Multi-use spaces with adjustable layouts: Flexible zoning is key to adapting spaces to daily activities. For instance, in an office setting, conference rooms can be designed with movable partitions and modular furniture that allow the space to shift from collaborative meetings to quiet work sessions. This flexibility supports varying levels of engagement and movement within the same area.

(3) Transition zones: Areas between different activity zones should facilitate smooth transitions without abrupt changes in movement. Transition zones, such as hallways, should be comprehensive and open to ensure easy movement from one part of the space to another. In retail environments, for instance, the transition between high-traffic shopping zones and quieter seating areas should be clear and inviting, encouraging users to move seamlessly between different experiences.

(4) Zoning based on sensory needs: Dynamic zones can also be created based on sensory experience. For example, focused work or relaxation areas may have muted colors, softer lighting, and sound-absorbing materials to minimize distractions. In contrast, high-energy spaces like gyms or social areas can be more vibrant, with brighter lighting and energetic colors that promote activity and engagement.

(5) Spatial adaptation for time-sensitive uses: In spaces like airports, public parks, or universities, zoning can shift based on the time of day and expected activity levels. High-traffic zones might expand or contract based on peak usage hours, while quieter zones become more prominent during off-hours. This adaptability

enhances the overall functionality of a space, ensuring it meets user needs throughout different periods of use.

6.3. Adapting designs for varied user groups

Designing spaces for diverse users—such as children, elderly individuals, and people with disabilities—requires thoughtful consideration of varying needs and physical capabilities. Inclusive design ensures that everyone can interact with a space comfortably and safely, regardless of age, mobility, or ability.

(1) Child-friendly designs: Spaces intended for children should account for smaller body sizes, different levels of mobility, and greater energy levels. In schools or playgrounds, furniture such as desks, chairs, and play equipment should be scaled down to fit children's proportions, ensuring ease of use and safety. Safety features like rounded edges, soft flooring, and stable surfaces should be incorporated to reduce injury risks during play or learning.

(2) Designing for the elderly: Spaces that cater to older adults should focus on accessibility, comfort, and safety. For example, handrails, grab bars, and ramps should be strategically placed in bathrooms, staircases, and walkways. Seating should be firm and supportive, with armrests that aid standing and sitting. Pathways should be free of obstacles and have non-slip surfaces to reduce the risk of falls, while lighting should be ample and glare-free to accommodate visual impairments that are common with age.

(3) Accommodating people with disabilities: Spaces should be universally accessible, ensuring that individuals with physical, sensory, or cognitive disabilities can navigate and use the space with ease. For wheelchair users, doors should be wide enough to accommodate entry, counters should be lowered, and paths should be free of obstructions. Visual and tactile signage, as well as auditory cues, can assist individuals with sensory impairments. Automated doors, adjustable workstations, and accessible bathroom facilities are essential for creating inclusive environments.

(4) Flexible design for multiple users: By incorporating flexible elements, multi-use spaces should accommodate various body types and abilities. For example, in public spaces like libraries or airports, seating should include a mix of styles—some with armrests and higher backs for additional support and others without, to suit different preferences and physical needs. Adjustable desks and tables, as well as accessible technology interfaces, ensure that the space remains usable by all.

(5) Universal design principles: Designers should adhere to universal design principles, prioritizing ease of use, accessibility, and inclusivity from the outset. This means that spaces are not retrofitted for accessibility but are built to be inclusive from the ground up, with features that cater to diverse user groups without requiring specialized accommodations. This approach ensures that spaces are functional and welcoming for everyone, regardless of ability.

7. Challenges and future directions

7.1. Limitations of current design approaches

While integrating HBD into SD has proven benefits, several challenges and limitations hinder its widespread adoption. These limitations stem from cost, complexity, and limited access to data, all of which can pose significant barriers to fully optimizing spaces according to human movement and ergonomics.

(1) Cost and budget constraints: One of the primary challenges in integrating detailed HBD analysis into SD projects is the cost. Advanced tools, such as motion capture systems, gait analysis technologies, and biomechanical simulations, require significant investment in both hardware and software. Moreover, hiring experts in biomechanics or ergonomics to analyze data and develop design recommendations can drive up project costs. In many cases, developers or clients may prioritize immediate budgetary concerns over the long-term benefits of investing in designs that optimize HBD, leading to compromises in functionality and user comfort.

(2) Design complexity: Integrating HBD into design complicates the planning and implementation processes. Designers must consider various factors—such as posture, range of motion, and physical strain—when determining furniture placement, pathway dimensions, or material selection. This complexity is especially pronounced in multi-use spaces that must accommodate various body types and activity levels. Managing these variables requires advanced tools and expertise, which can be challenging to streamline in traditional design workflows. This complexity can become a significant barrier for smaller projects or firms lacking the resources to integrate biomechanics fully.

(3) Limited data on diverse populations: Another challenge is the limited availability of comprehensive data representing the wide range of body types and movement patterns across different populations. Many design guidelines are based on anthropometric data that may not fully account for age, gender, disability, and cultural variations in movement behavior. Without accurate data, it cannot be easy to create genuinely inclusive designs that meet the needs of all users. Additionally, the high variability in human movement, such as differences in gait or posture across individuals, further complicates the application of HBD in SD.

(4) Technological barriers: While technological advancements have made it easier to analyze human movement, not all design firms can utilize these tools effectively. Technologies like virtual reality (VR) and artificial intelligence (AI), which can simulate and predict movement in designed spaces, are still developing. The lack of widespread access to these technologies, coupled with the steep learning curve for implementation, creates a gap between what is theoretically possible and what is practical in everyday design scenarios.

(5) Balancing aesthetic and functional goals: Designers often face balancing aesthetic goals with the functional needs that HBD analysis suggests. For example, while ergonomic furniture may be optimized for body comfort, it may not always align with a designer’s aesthetic vision or the client’s preferences. This tension between form and function can lead to compromises that detract from the overall usability of a space.

7.2. Future research opportunities

Despite the current limitations, technological advancements and an increasing focus on user-centered design present exciting opportunities for future research in HBD and SD. The following are key areas for future exploration:

(1) Advancements in AI for dynamic space optimization: Artificial intelligence (AI) and machine learning (ML) hold enormous potential for improving space optimization based on HBD. AI systems can analyze large datasets from motion capture or wearable sensors to identify patterns in how people move through different environments. By processing this data, AI can help designers predict a space's use and suggest improving layouts, materials, and overall functionality. Future research could focus on developing AI algorithms that adapt to real-time feedback from users, enabling spaces to adjust based on activity levels or environmental conditions automatically.

(2) Biomechanics in virtual design environments: Integrating biomechanics into virtual design environments offers a promising area for future research. Tools like VR and augmented reality (AR) allow designers to simulate how people will move through a space before it is built. Future advancements could enable more precise modeling of individual HBD, considering factors such as joint mobility, muscle fatigue, or posture under different conditions. This would allow designers to test and refine layouts in a virtual space, optimizing for comfort and movement efficiency.

(3) Wearable technology for real-time movement analysis: Wearable devices, such as smart clothing or sensors, offer real-time data on HBD, providing valuable insights into how individuals interact with their environments. Future research could explore how this data can be integrated into the design process, allowing for ongoing adjustments based on how users move through a space. This continuous feedback loop could lead to spaces that evolve, adapting to the changing needs of occupants.

(4) Inclusive design for diverse populations: Given the limitations of current anthropometric data, future research could focus on gathering more detailed and diverse datasets that reflect a broader range of human body types, ages, and physical abilities. These datasets could inform the development of more inclusive design guidelines that accommodate the needs of all users. Additionally, research into how different populations engage with space could uncover new strategies for making public and private spaces more accessible and user-friendly.

(5) Neuroscience and human interaction in space: An emerging area of research is the intersection between neuroscience and SD. Researchers can gain deeper insights into how people experience and interact with spaces by studying how the brain processes spatial information and movement. This research could lead to designs that support physical movement and enhance cognitive and emotional well-being. For example, specific SD or environments may reduce stress or improve focus, creating more engaging and productive spaces.

(6) Sustainability and movement efficiency: Future research could explore how HBD intersects sustainable design practices. For instance, optimizing pathways for energy-efficient movement—such as reducing the need for elevators or escalators

in favor of well-designed ramps or staircases—could contribute to greener building designs. By analyzing how human movement can be aligned with sustainable principles, designers could create environmentally responsible and comfortable spaces for users.

(7) Automation in data collection and analysis: Automating the process of collecting and analyzing data on HBD could make it more feasible for smaller firms or projects with limited budgets to integrate these insights into their designs. Future research could focus on developing affordable, easy-to-use tools for capturing and processing movement data. This could democratize access to advanced design techniques and allow for wider adoption of HBD principles in everyday projects.

8. Conclusion and future work

Integrating HBD into interior and landscape design is essential for creating environments that are functional, comfortable, and accessible to a wide range of users. This paper has demonstrated that by understanding and applying key concepts such as biomechanics, posture, gait, and balance, designers can optimize spatial arrangements to support natural human movement, enhance efficiency, and reduce the risk of physical strain. Through case studies and methods such as motion capture, gait analysis, and ergonomic assessments, this research has provided practical insights into how spaces can be designed to accommodate the diverse physical needs of users, including children, older adults, and individuals with disabilities. While the benefits of incorporating HBD into the SD are clear, widespread adoption still has challenges, including the cost and complexity of the necessary tools and limited access to comprehensive data on diverse populations. However, technological advancements, particularly in artificial intelligence and wearable sensors, offer promising future research and innovation opportunities. These tools can enable designers to create dynamic, adaptive spaces that respond to real-time user data, allowing for continuous optimization of comfort and functionality. In conclusion, applying HBD to SD represents a significant step in creating environments that enhance physical well-being and user satisfaction. By considering individuals' natural movements and physical interactions, designers can create aesthetically pleasing spaces that support the body's physical needs.

This approach to design benefits individual users and promotes inclusivity, accessibility, and sustainability in both public and private spaces.

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